



SLS

Space Launch System

Space Launch System Implementation of Adaptive Augmenting Control

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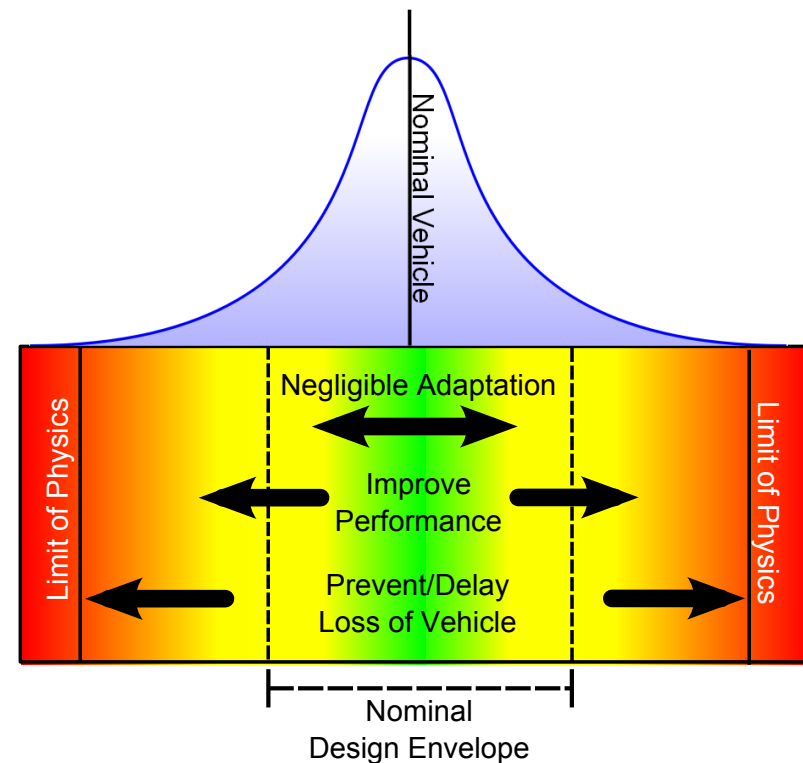
- ◆ **Adaptive Augmenting Control (AAC) has been developed for exploration class manned launch vehicles during the Constellation program [2]**
- ◆ **The AAC concept has been developed for NASA's Space Launch System family of launch vehicles and implemented as a baseline part of its full-scale flight control software**
- ◆ **SLS implementation of AAC has been dispersion tested in multiple simulation environments, flight tested using Dryden's specially outfitted F/A-18 test bed [3], and is fast approaching a CDR level of maturity**
- ◆ **Presentation will describe**
 - Basics of adaptive formulation
 - Changes to Original AAC for SLS
 - Application to SLS Control system
 - Simulation Results
 - Stressing Cases
 - Monte Carlo Analysis



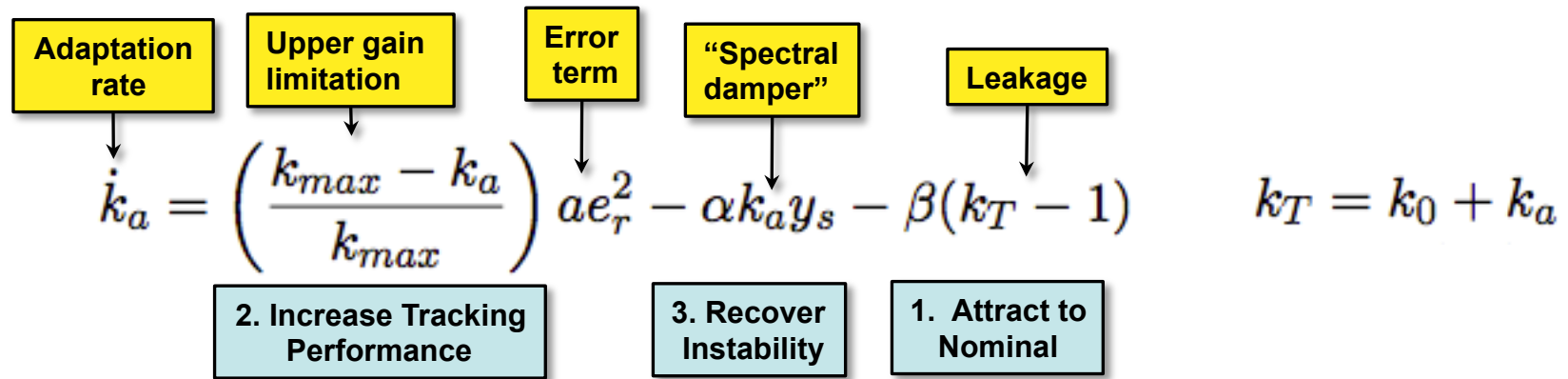
- ◆ Extends performance and robustness of baseline gain-scheduled (“fixed gain”) control system for the conditionally stable launch vehicle
- ◆ Augmentation uses sensed data to adjust the total loop gain on-line

◆ AAC summary-level design objectives:

1. “Do no harm”; return to baseline control design when not needed
2. Respond to error within ability of vehicle to track commands to increase performance
3. Respond to undesirable parasitic dynamics (i.e., control-structure interaction) to regain stability

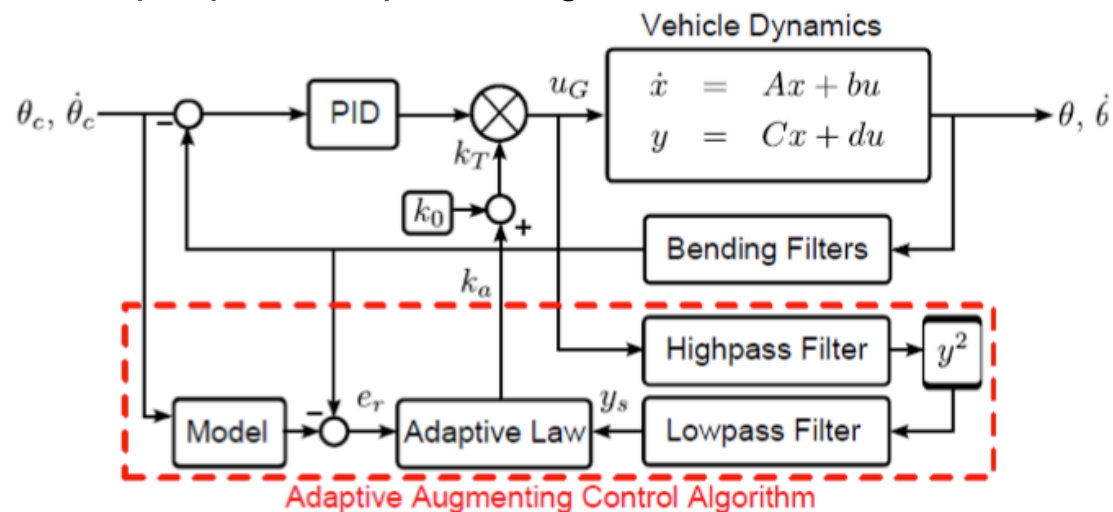


- ◆ Original adaptive gain law [2] features three components corresponding to the three objectives



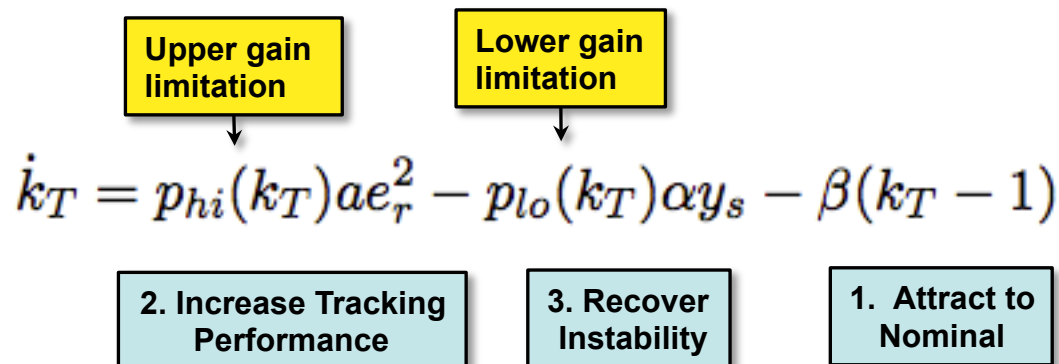
- ◆ Total Gain resulting from adaptation applied to PID control signal

- AAC reference model provides error signal to gain up control
- AAC spectral damper provides power to gain down control



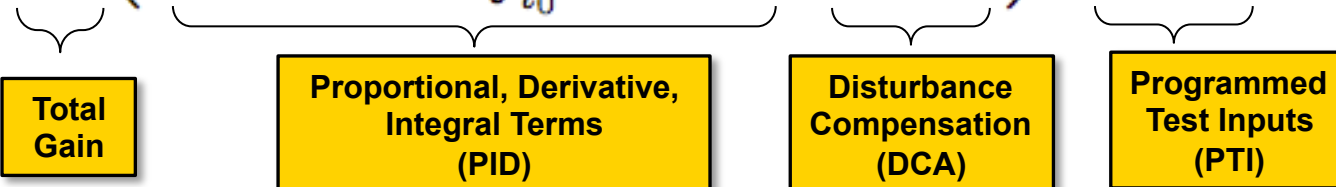
$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}} \right) a e_r^2 - \alpha k_a y_s - \beta (k_T - 1) \quad k_T = k_0 + k_a$$

- ◆ SLS implementation carries three terms matching the original three objectives but with updates to the formulation



- ◆ Right hand nonlinear dependencies on adaptation gain have been removed
 - Provides for a more linear response of gain adaptation to inputs
- ◆ Employed parameterized saturation functions to allow tunability of adaptation response to inputs
 - Can yield a more rapid adaptation response than in the original formulation
 - SLS parameterized to effect a rapid, linear, response within 90% of allowable gain range
- ◆ Adaptive law has been recast directly in terms of total gain
 - Simplification of expression and flight code

- ◆ **Baseline controller issues single angular acceleration command to the control allocator (OCA) per axis (pitch axis “q” shown)**

$$\dot{q}_c = k_T \left(k_p \theta_e + k_d \dot{q}_e + \int_{t_0}^{t_0+t} k_i \theta_e d\tau + \dot{q}_{DCA} \right) + \dot{q}_{PTI}$$


The equation is annotated with four yellow boxes below it, each connected by a bracket to a specific part of the equation:

- Total Gain**: Points to the k_T term.
- Proportional, Derivative, Integral Terms (PID)**: Points to the terms $k_p \theta_e + k_d \dot{q}_e + \int_{t_0}^{t_0+t} k_i \theta_e d\tau$.
- Disturbance Compensation (DCA)**: Points to the \dot{q}_{DCA} term.
- Programmed Test Inputs (PTI)**: Points to the \dot{q}_{PTI} term.

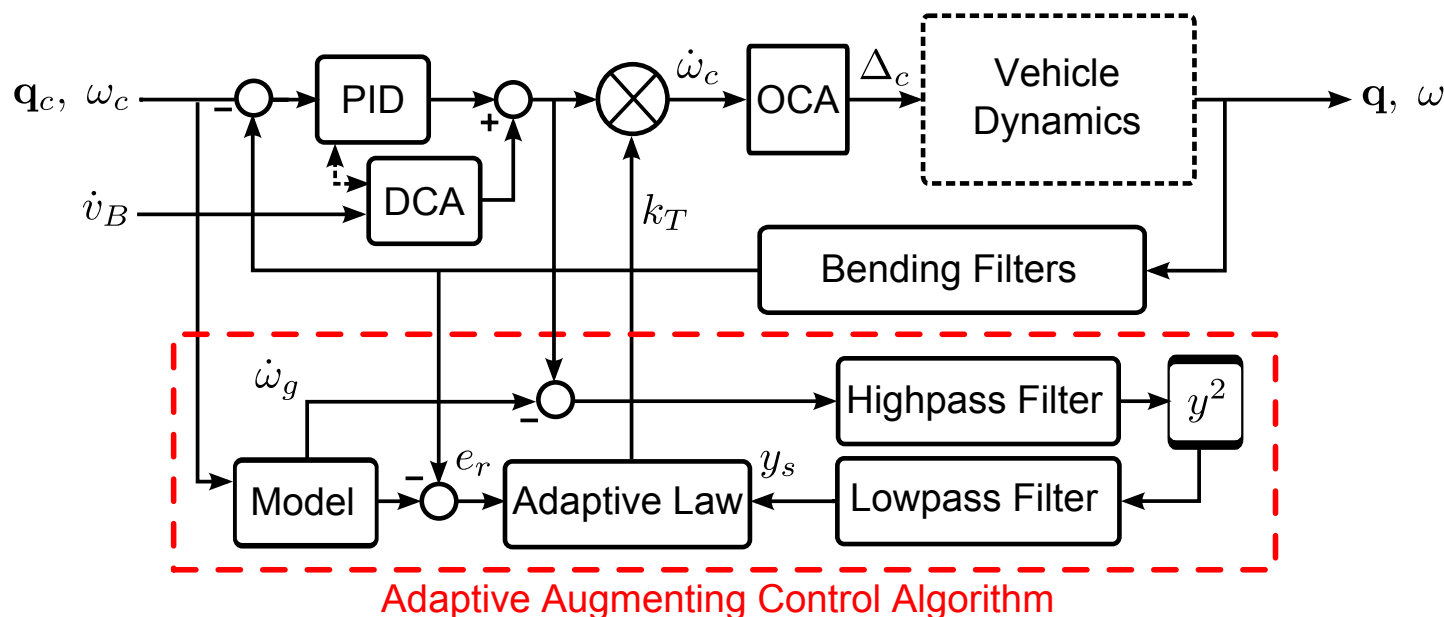
- ◆ **Total gain is adjusted by adaptive law and applied to PID & DCA terms**
- ◆ **Application to DCA aids in two ways**
 - Objective 2: increases disturbance rejection performance, maintains PID/DCA gain ratios
 - Objective 3: allows adaptation decrease for parasitic dynamics in DCA loop
- ◆ **PTI is excluded from total gain**
 - Open loop table-lookup input for the purpose of flight test system identification
- ◆ **Angular acceleration command is the point at which SISO open loop (OL) response is constructed**
 - Total gain adjustments shifts the forward gain of the entire OL transfer function

◆ Baseline Control System

- PID – (proportional, derivative, integral)
 - Quaternion and rate commands
- Bending Filters – attenuates, phases parasitic dynamics (flex, slosh, actuator lag)
- DCA (Disturbance Compensation Algorithm)
 - Rate and acceleration inputs
- OCA (Optimal Control Allocator) – linear allocator based on weighted least-squares

◆ Adaptive Augmenting Control

- Reference model
- Spectral damper process (filters, rectification)
- Adaptive Law

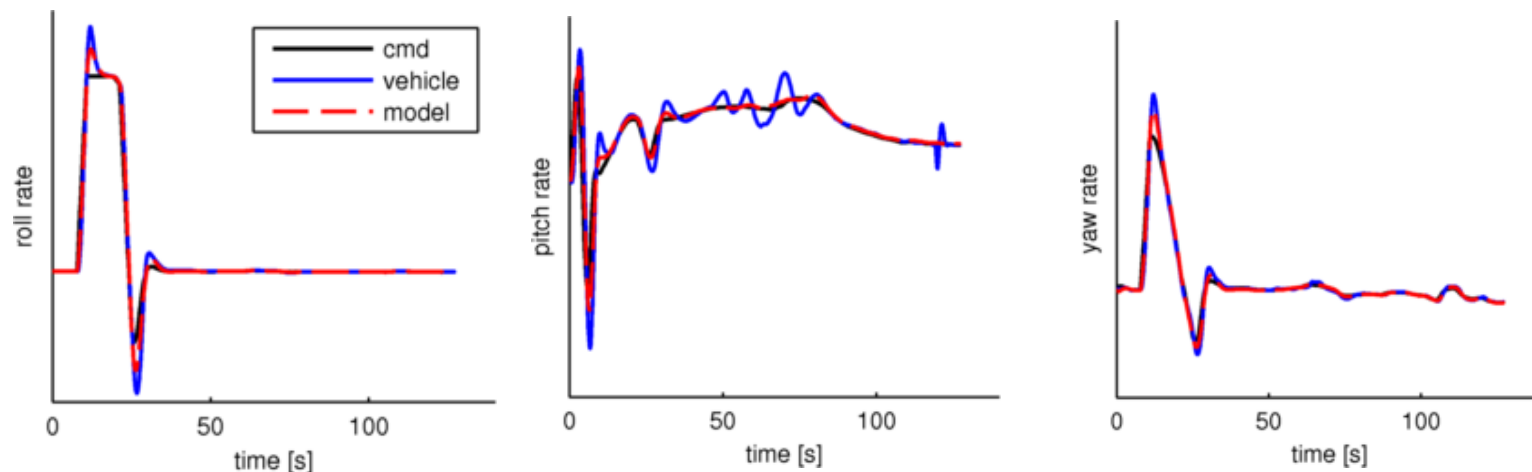


- $$H_r(s) = e^{-s\tau} \frac{\omega_r^2 + 2\zeta_r \omega_r s}{s^2 + 2\zeta_r \omega_r s + \omega_r^2}$$



◆ **Reference model response compares well to actual system system**

- Rate response for each axis shown on different scale
- Roll shows largest commands during first half of boost phase trajectory
- Pitch shows initial tower avoidance maneuver and day-of-launch wind adjustments
- Yaw axis shows smallest command (cross-axis coupling during maneuvers)



◆ **Reference model response is compared to actual vehicle response to generate error signals indicating the extent to which rigid body control response has deviated from nominal/desired**

$$\dot{\gamma}_r = \hat{\omega} - \omega \quad \gamma_r = \hat{\Theta} - \Theta$$

◆ **Rate errors and attitude errors are blended together for each axis to produce a single signal in each axis to effect an adaptation gain increase in the corresponding axis**

$$e_r = c\gamma_r + \dot{\gamma}_r$$

- ◆ Spectral damper, consistent with the original formulation, provides an estimate of the power of undesirable frequency content in the feedback path
- ◆ Input signal is constructed from the angular acceleration control command
 - Taken prior to application of total loop gain (avoids direct gain-induced transients)

$$\dot{q}_c = \cancel{k_T} \left(k_p \theta_e + k_d q_e + \int_{t_0}^{t_0+t} k_i \theta_e d\tau + \dot{q}_{DCA} \right) + \cancel{\dot{q}_{FTI}}^0$$

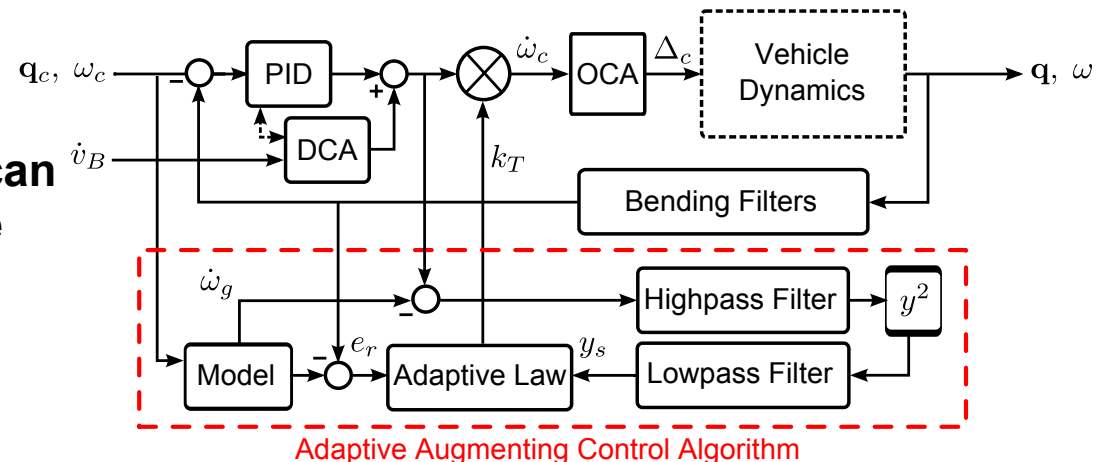
- Includes DCA to capture undesirable dynamics in its feedback paths
- Subtracts a angular acceleration compensation term based upon the reference model dynamics to account for guidance-induced control commands

$$\dot{q}_g = \omega_r^2 (\theta_c - \hat{\theta}) + 2\zeta_r \omega_r (q_c - \hat{q})$$

- ◆ Resultant signal is then band-passed, squared, and low-passed to provide a smooth positive signal used to effect an adaptation gain decrease

- ◆ Filter parameters selected to highlight frequency spectrum associated with dynamics which can be suppressed by a gain decrease

- propellant slosh
- structural flexibility
- actuator dynamics



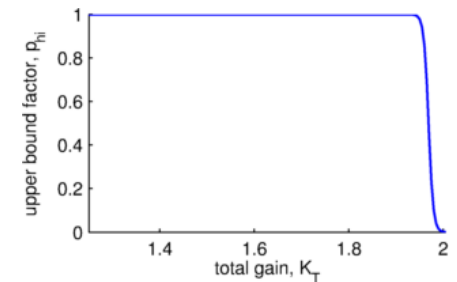
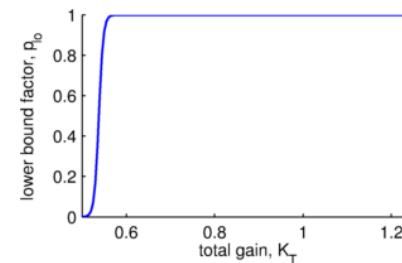
◆ Saturation Functions Applied to Squared Error and Spectral Inputs

- Smooth saturation at ends of total gain range with tunable shape

$$\dot{k}_T = p_{hi}(k_T)ae_r^2 - p_{lo}(k_T)\alpha y_s - \beta(k_T - 1)$$

$$p_{hi}(k_T) = 1 - \left(1 + \exp \left[A \left(\frac{1}{A} \log \left(\frac{\epsilon k_{Tmax}}{1 - \epsilon k_{Tmax}} \right) + k_{Tmax} - k_T \right) \right] \right)^{-1}$$

$$p_{lo}(k_T) = \left(1 + \exp \left[A \left(\frac{1}{A} \log \left(\frac{1 - \epsilon k_{Tmax}}{\epsilon k_{Tmax}} \right) + k_{Tmin} - k_T \right) \right] \right)^{-1}$$



◆ Explicit hard limits are additionally imposed on total gain

- 0.5 and 2.0 are current SLS total gain limits
- correspond to -/+ 6 dB nominal gain margin design criteria

◆ Adaptive rate limits imposed on squared error and spectral inputs

- Parameterized by the time for the term to effect a full scale gain change
- Safeguards to preclude numerical problems due to large or spurious inputs

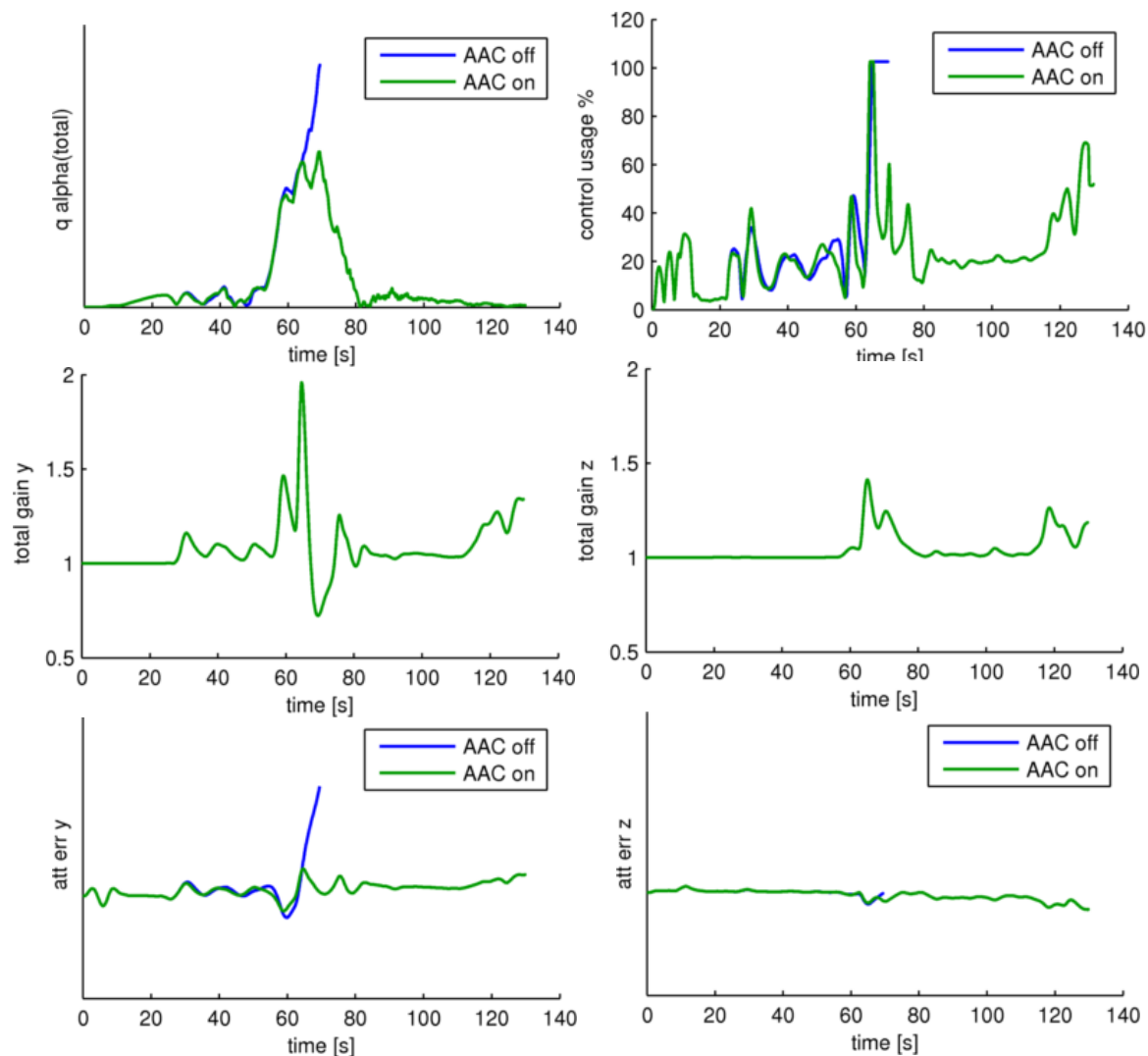
$$e_{lim}^2 = \left(\frac{k_{Tmax} - k_{Tmin}}{a\Delta t_{elim}} \right) \quad y_{slim} = \left(\frac{k_{Tmax} - k_{Tmin}}{\alpha\Delta t_{sdlim}} \right)$$

◆ Squared error and spectral signal are forced to be positive

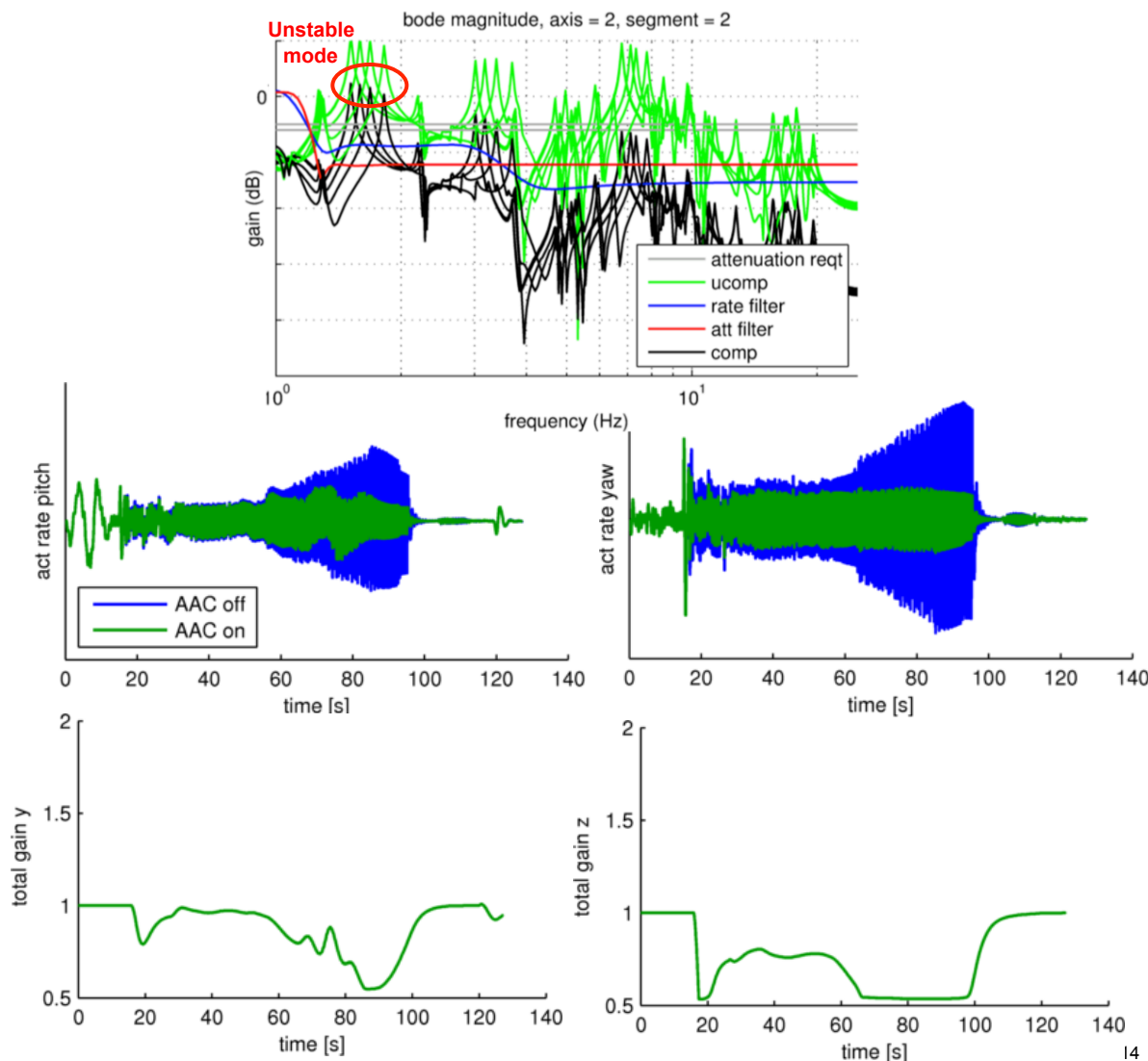
- Spectral signal can be negative for low pass filters with complex poles

- ◆ **SLS AAC has been enabled for the boost phase of flight although plans exist to explore its extension through core stage flight**
- ◆ **The SLS FCS including AAC has been implemented in four main simulation tools:**
 - ◆ **MAVERIC (Marshall Aerospace Vehicle Representation In C)**
 - MSFC developed 6-DOF time-domain simulation
 - Main ascent performance, guidance, navigation and control analysis tool
 - ◆ **CLVTOPS (Crew Launch Vehicle Tree tOPology)**
 - Multi-body simulation built upon legacy TREETOPS tool
 - Employed for dispersed vehicle liftoff and staging separation clearance analysis
 - ◆ **SAVANT (Stability Aerospace Vehicle ANalysis Tool)**
 - Simulink-based Verification and Validation Tool for SLS
 - ◆ **STARS (Space Transportation Analysis and Research Simulation)**
 - NASA Langley developed, main simulation for Ares I-X
 - Simulink-based Verification and Validation Tool for SLS
- ◆ **Results using MAVERIC tool are shown in the following slides**
 - Stressing case demonstrating objectives 1 and 2
 - Stressing case demonstrating objectives 1 and 3
 - PDR Monte Carlo Analysis results

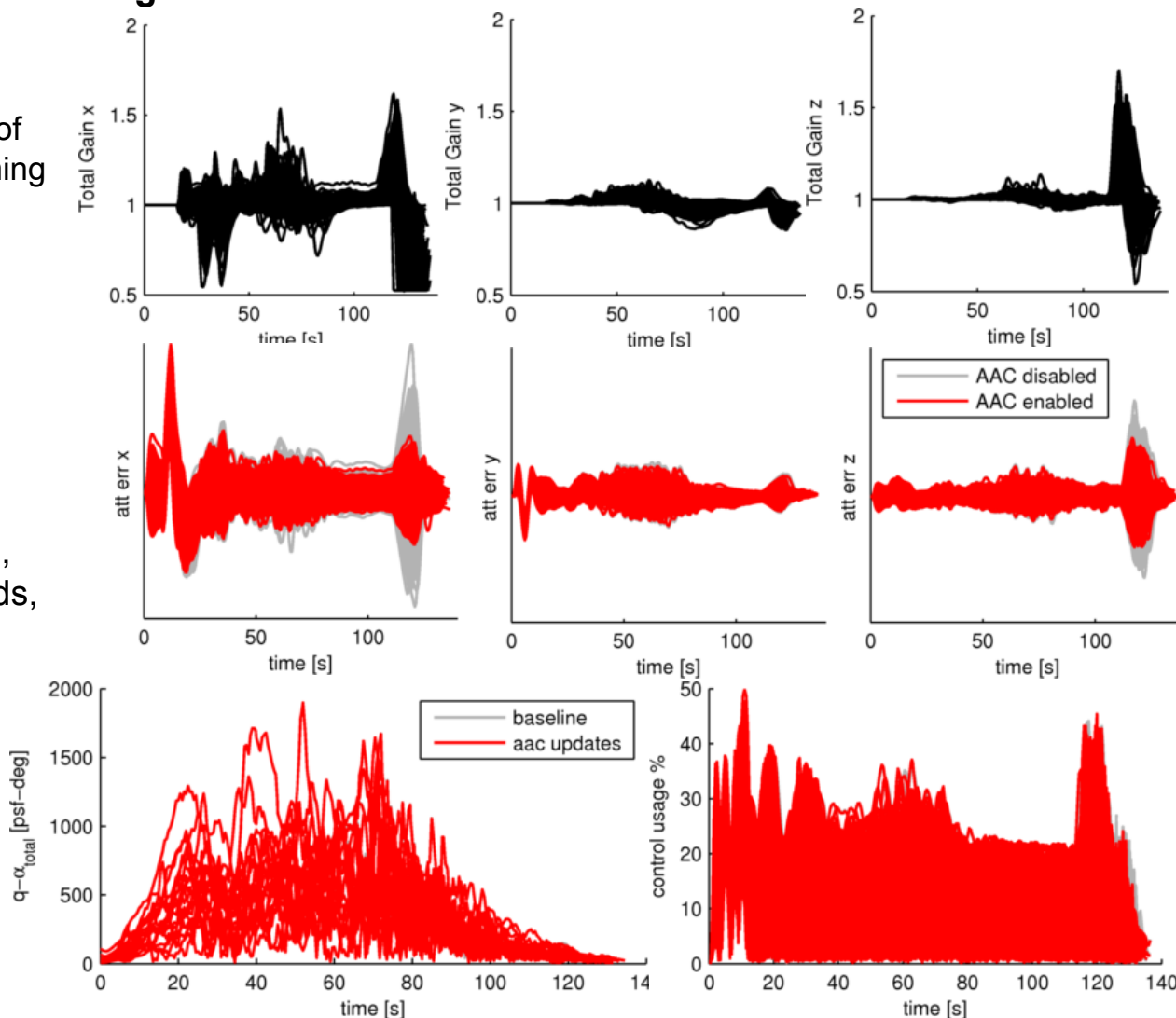
- ◆ **Example case: increased aerodynamic instability, severe winds, and a single-engine dual actuator hardover occurring during maximum dynamic pressure**
- ◆ **Extreme scenario with AAC off results in a violation of the rigid body load indicator (dynamic-pressure * total angle of attack) limit**
 - Plot terminates
- ◆ **AAC gains up the system at the onset of the disturbances**
 - Greatly improves attitude tracking
 - Load indicator stays well below limit
 - Control effort only temporarily saturates
- ◆ **AAC gain returns to nominal unity value after disturbances subside (objective 1)**



- ◆ **Example case: primary structural mode undergoes simulated instability during region of flight where gain of mode is higher than necessary attenuation provided by control filters**
- ◆ **Extreme scenario with AAC off results in divergent behavior in the actuator rates**
- ◆ **AAC gains down the system at the onset of the instability**
 - Suppresses modal response to a limit cycle of non-destructive magnitude
- ◆ **AAC gain returns to nominal unity value after instability ceases to persist (objective 1)**



- ◆ **Example Monte Carlo simulation from liftoff to booster separation (2000 runs)**
- ◆ **Dispersions include but not limited to mass properties, structural dynamics, sensor noise, aerodynamics, winds, thrust misalignment**
- ◆ **Total gain in pitch shows minimal adaptation**
 - Small deviation towards end of flight due to booster tailoff timing variations
- ◆ **Yaw shows adaptation in booster tail-off region**
 - Corresponding to highly dispersed booster thrust imbalance
- ◆ **Roll shows the most adaptation**
 - Large guidance commands, excursions due to high winds, booster tailoff, and conservative booster slag model
- ◆ **Overall, minimal effect on load indicators and control usage despite vehicle and environment design dispersions (objective 1)**





Questions?



- ◆ [1] J. Orr, J. Wall, T. VanZwieten, and C. Hall, “Space Launch System Ascent Flight Control Design,” in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.
- ◆ [2] J.Orr and T.VanZwieten, “Robust, Practical Adaptive Control for Launch Vehicles,” in *AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, AIAA-2012-4549*, August 2012.
- ◆ [3] T. VanZwieten, E. Gilligan, J. Wall, and J. Orr, “Adaptive Augmenting Control Flight Characterization Experiment on an F/A-18,” in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.
- ◆ [4] J. Orr, “Optimal Recursive Digital Filters for Active Bending Stabilization,” in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2013.
- ◆ [5] J. Hanson and C. Hall, “Learning About Ares I from Monte Carlo Simulation,” in *AIAA Guidance, Navigation, and Control Conference, Honolulu, HI, AIAA-2008-6622*, 2008.